

Gamma-ray bursts and their relation to astroparticle physics and cosmology

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This article gives an overview of gamma-ray bursts (GRBs) and their relation to astroparticle physics and cosmology. GRBs are the most powerful explosions in the universe that occur roughly once per day and are characterized by flashes of gamma-rays typically lasting from a fraction of a second to thousands of seconds. Even after more than four decades since their discovery they still remain not fully understood. Two types of GRBs are observed: spectrally harder short duration bursts and softer long duration bursts. The long GRBs originate from the collapse of massive stars whereas the preferred model for the short GRBs is coalescence of compact objects such as two neutron stars or a neutron star and a black hole. There were suggestions that GRBs can produce ultra-high energy cosmic rays and neutrinos. Also a certain sub-type of GRBs may serve as a new standard candle that can help constrain and measure the cosmological parameters to much higher redshift than what was possible so far. I will review the recent experimental observations.

Keywords: gamma-ray bursts; astroparticle physics; cosmology

1. Gamma-Ray Bursts

This section briefly overviews the gamma-ray burst (GRB) phenomena^{1–5}. GRBs are one of the most extreme explosive events ever observed. They were discovered in late sixties and reported to the scientific community in early seventies^{6,7}. In spite of tremendous effort and numerous observations there are still open questions concerning their detailed physics. They occur roughly once per day and are characterized by flashes of γ -rays typically lasting from a fraction of a second to thousands of seconds, see Fig. 1(a). It has been found that the duration distribution of their γ -ray prompt emission is bimodal⁸ which suggested that there were two groups of GRBs, see Fig. 1(b). Later, based on more observations, it has been confirmed that these two GRB groups were two distinct astrophysical populations: I. so called long GRBs with prompt γ -ray emission $\gtrsim 2$ s that has been identified to be gravitational collapses of massive stars due to their association with type Ic core-collapse supernovae, and II. so called short GRBs with prompt γ -ray emission $\lesssim 2$ s that has been suggested to originate in a merger of two compact objects such as NS-NS or NS-BH⁹. It was proposed that they lie at cosmological distances¹⁰ and they are created in collisions of highly relativistic outflow of the accelerated jetted matter^{11,12}. In many cases it was found that the prompt γ -ray emission is followed by longer-lasting afterglow in soft X-ray, optical or radio waves^{13,14} explained as a result of the interaction of the relativistic outflow with the circum-burst

medium. Observations found that their redshifts are up to $z = 9.4$ with $\langle z \rangle \approx 0.5$ for short GRBs and $\langle z \rangle \approx 2.0$ for long GRBs⁹ which requires energy release up to an isotropic-equivalent value of $\sim 10^{54}$ erg.

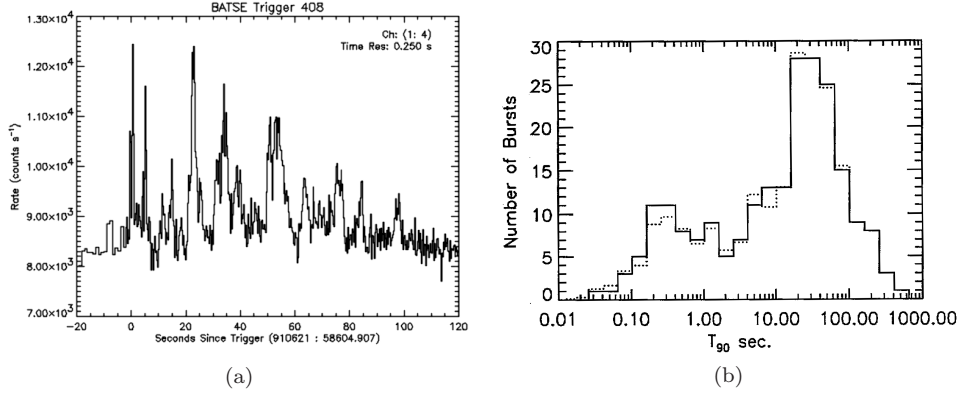


Fig. 1. (a) An example of GRB prompt gamma flux curve detected by BATSE instrument. From ref. ¹⁵. (b) The distribution of T_{90} durations of GRBs indicating two distinct groups. From ref. ⁸

2. Relation of GRBs to Cosmology

There were discovered several correlations in the properties of the GRB emission: the anti-correlation between isotropic luminosity L_{iso} and spectral lag τ_{lag} of the prompt γ -ray emission¹⁶; the correlation between L_{iso} and light-curve variability V ¹⁷; the spectral peak energy of the prompt γ -ray emission E_{peak} and isotropic-equivalent released energy E_{iso} correlation¹⁸, see Fig. 2(a); E_{peak} and collimated energy E_{γ} correlation¹⁹; E_{peak} and peak luminosity L_p correlation²⁰; correlation between E_{peak} , E_{iso} and rest-frame temporal break in optical afterglow light curve t_{break} ²¹; and a correlation between L_{iso} , E_{peak} and prompt 'high-signal' time-scale $T_{0.45}$ (variability)²². This makes GRBs a potential tool to constrain cosmological parameters^{23–26}, see Fig. 3(a).

It was also found that the peak flux F_p (at 2 eV and $z = 2$) might anti-correlate with peak time t_p in the optical lightcurves^{27–29}, see Fig. 2(b). A similar anti-correlation for the peak luminosity in R band of the onset bumps and less steep for the re-brightening bumps in the optical lightcurves was found³⁰. Unfortunately for many observations the peak time t_p is unknown and further optical observations at earlier times are needed.

More early optical observations with fine sampling of the light curves around the peak times below one minute could be provided by the Ultra-Fast Flash Observatory pathfinder (UFFO-p)^{31–33}. It is a novel spaceborn instrument dedicated to detect GRBs and rapidly follow their optical/ultraviolet counterparts to provide prompt optical and early afterglow measurements. It consists of two scientific instruments,

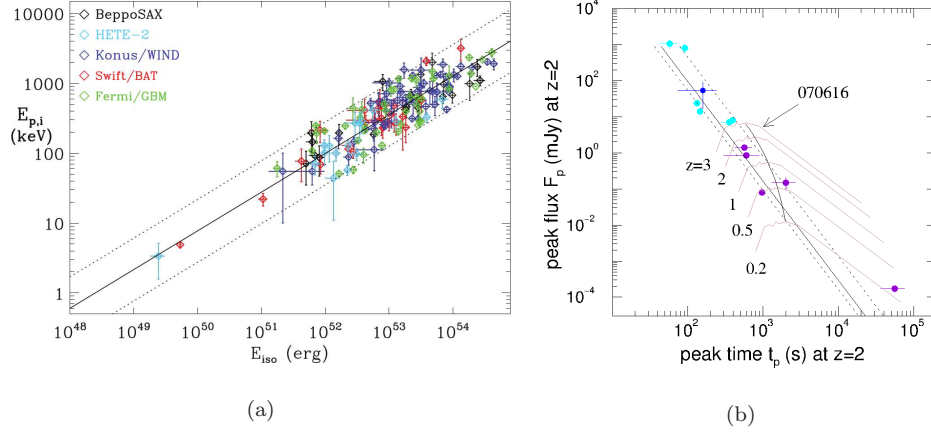


Fig. 2. (a) The $E_{p,i} - E_{iso}$ correlation for long GRBs with marked best-fit power-law (black solid line) for different instruments. From ref.²⁶ (b) The anti-correlation of optical light-curve peak flux (at 2 eV) for redshift $z = 2$ and peak time for six fast rising afterglows (light blue points) and five afterglows slow rising (purple points). The solid straight line shows the best fit. From ref.²⁷

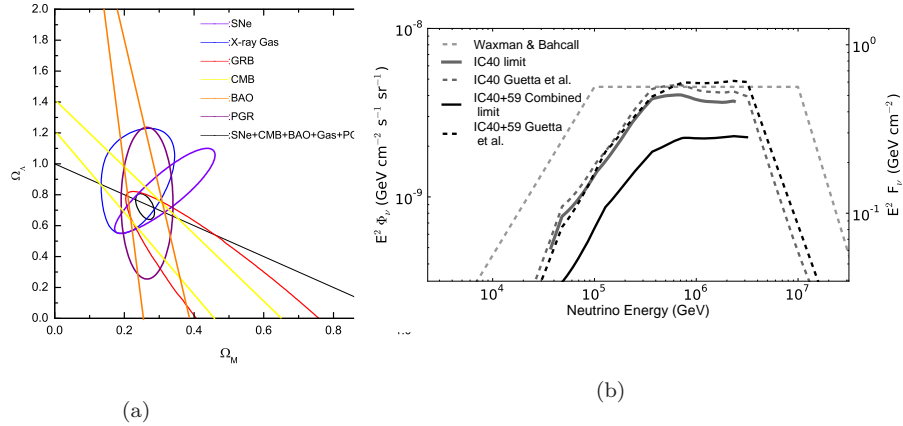


Fig. 3. (a) Joint 1σ confidence intervals given by constraints from the datasets of galaxy clusters, GRBs, CMB shift parameter, SNe Ia, BAO, and 2dF Galaxy Redshift Survey. From ref.^{24,25} (b) Comparison of predictions of ν flux from GRBs based on observed γ -ray spectra (dashed lines) with 90 % confidence upper limits obtained from the results of IceCube for 40 and 59 detector strings. From ref.⁵⁰

see Fig. 4. A GRB location is determined in a few seconds by the first instrument called UFFO Burst Alert & Trigger telescope (UBAT)^{34–37} which employs the coded mask imaging technique³⁸ and the detector comprising of Yttrium Oxy-orthosilicate scintillating crystals and multi-anode photomultiplier tubes. It has the energy range of $\approx 10 - 150$ keV with half-coded field of view (HCFOV) $70.4^\circ \times 70.4^\circ$ and angular resolution $\leq 10'$. The second instrument is the Slewing Mirror Tele-

scope (SMT)^{39–42} with the field of view of $17' \times 17'$ and UV range of 200–650 nm. It consists of a Ritchey-Chrétien telescope with an Intensified Charge-Coupled Device in its focal plane. In front of the telescope there is placed a fast plane slewing mirror which allows to redirect the optical path and start observation within ≈ 1 s since it receives the target direction. SMT slewing mirror provides approximately the same sky coverage as UBAT's HCFOV. UBAT and SMT have been assembled and integrated with the control electronics on UFFO-p which is planned to be launched on the Lomonosov Moscow State University satellite⁴³.

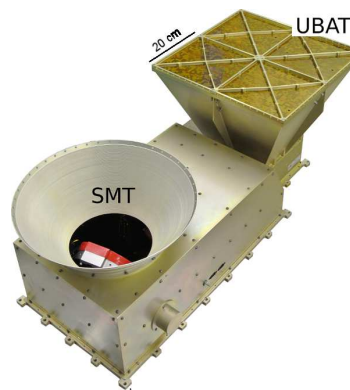


Fig. 4. The photo shows assembled UFFO-p with its two scientific instruments: UBAT and SMT. From ref.³⁷

3. Relation of GRBs to Astroparticle Physics

GRBs were proposed to be sites for accelerating ultra-high energy cosmic rays and sources of very high energy neutrinos up to $10^{17} \sim 10^{19}$ eV^{44–48}. However, the recent results from the IceCube detector⁴⁹ suggests that the efficiency of neutrino production may be much lower than predicted⁵⁰. 4-years data of IceCube put constraints on the prompt neutrino flux from GRBs, see Fig. 3(b). A single low-significance neutrino, compatible with the atmospheric neutrino background, was found in coincidence with one of the 506 observed GRBs⁵¹.

References

1. T. Piran, The physics of gamma-ray bursts, *Rev. of Mod. Phys.* **76**, 1143 (2004).
2. P. Mészáros, Gamma-ray bursts, *Rep. on Prog. in Phys.* **69**, 2259 (2006).
3. N. Gehrels and S. Razzaque, Gamma-ray bursts in the swift-Fermi era, *Frontiers of Physics* **8**, 661 (2013).
4. G. Vedrenne and J.-L. Atteia, Gamma-Ray Bursts, *Gamma-Ray Bursts: The Brightest Explosions in the Universe* (Springer Praxis Books, Springer-Verlag Berlin, 2009).

5. C. Kouveliotou, R. A. M. J. Wijers and S. Woosley, Gamma-ray Bursts, *Gamma-ray Bursts* (Cambridge University Press, Cambridge, UK, 2012).
6. R. W. Klebesadel, I. B. Strong and R. A. Olson, Observations of gamma-ray bursts of cosmic origin, *ApJ* **182**, L85 (1973).
7. E. P. Mazets, et al., Burst of cosmic gamma-emission from observations on Cosmos 461, *Pisma v Zhurnal Eksperimentalnoi i Teoreticheskoi Fiziki* **19**, 126 (1974).
8. C. Kouveliotou, C. A. Meegan, G. J. Fishman, et al., Identification of two classes of gamma-ray bursts, *ApJ* **413**, L101 (1993).
9. E. Berger, Short-duration gamma-ray bursts, *Annual Review of Astronomy and Astrophysics* **52**, 43 (2014).
10. B. Paczynski, Gamma-ray bursters at cosmological distances, *ApJ* **308**, L43 (1986).
11. M. J. Rees and P. Meszaros, Relativistic fireballs - Energy conversion and time-scales, *MNRAS* **258**, 41 (1992).
12. M. J. Rees and P. Meszaros, Unsteady outflow models for cosmological gamma-ray bursts, *ApJ* **430**, L93 (1994).
13. E. Costa, F. Frontera, J. Heise, et al., Discovery of an X-ray afterglow associated with the γ -ray burst of 28 February 1997, *Nature* **387**, 783 (1997).
14. J. van Paradijs, P. J. Groot, T. Galama, et al., Transient optical emission from the error box of the γ -ray burst of 28 February 1997, *Nature* **386**, 686 (1997).
15. G. J. Fishman, C. A. Meegan, R. B. Wilson, et al., The first BATSE gamma-ray burst catalog, *ApJS* **92**, 229 (1994).
16. Norris, J. P., G. F. Marani and J. T. Bonnell, Connection between energy-dependent lags and peak luminosity in gamma-ray bursts, *ApJ* **534**, 248 (2000).
17. E. E. Fenimore and E. Ramirez-Ruiz, Redshifts for 220 BATSE gamma-ray bursts determined by variability and the cosmological consequences, *arXiv:astro-ph/0004176* (2000).
18. L. Amati, F. Frontera, M. Tavani, et al., Intrinsic spectra and energetics of BeppoSAX Gamma-Ray Bursts with known redshifts, *A&A* **390**, 81 (2002).
19. G. Ghirlanda, G. Ghisellini and D. Lazzati, The collimation-corrected gamma-ray burst energies corr. with the peak ener. of their νF_ν spect., *ApJ* **616**, 331 (2004).
20. D. Yonetoku, T. Murakami, T. Nakamura, et al., Gamma-ray burst formation rate inferred from the spectral peak energy-peak luminosity relation, *ApJ* **609**, 935 (2004).
21. E.-W. Liang and B. Zhang, Model-independent multivariable gamma-ray burst luminosity indicator and its possible cosmological implications, *ApJ* **633**, 611 (2005).
22. C. Firmani, et al., Discovery of a tight correlation among the prompt emission properties of long gamma-ray bursts, *MNRAS* **370**, 185 (2006).
23. Ghirlanda, G., G. Ghisellini and C. Firmani, Gamma-ray bursts as standard candles to constrain the cosmological parameters, *New Journal of Physics* **8**, 123 (2006).
24. F. Y. Wang, Z. G. Dai and Z.-H. Zhu, Measuring dark energy with gamma-ray bursts and other cosmological probes, *ApJ* **667**, 1 (2007).
25. F. Y. Wang, Z. G. Dai and E. W. Liang, Gamma-ray burst cosmology, *New Astronomy Reviews* **67**, 1 (2015).
26. L. Amati and M. D. Valle, Measuring cosmological parameters with gamma-ray bursts, in *Proc. of the MG13 Meet. on General Relativity*, (World Scientific, Singapore, 2015), p. 769.
27. A. Panaitescu and W. T. Vestrand, Taxonomy of gamma-ray burst optical light curves: identification of a salient class of early afterglows, *MNRAS* **387**, 497 (2008).
28. A. Panaitescu and W. T. Vestrand, Optical afterglows of gamma-ray bursts: peaks, plateaus and possibilities, *MNRAS* **414**, 3537 (2011).
29. A. Panaitescu, W. T. Vestrand and P. Woźniak, Peaks of optical and X-ray afterglow light curves, *MNRAS* **433**, 759 (2013).
30. E.-W. Liang, L. Li, H. Gao, et al., A Comprehensive study of gamma-ray burst optical

- emission. II. Afterglow onset and late re-brightening components, *ApJ* **774**, 13 (2013).
31. P. Chen, S. Ahmad, K. B. Ahn, et al., The UFFO (Ultra Fast Flash Observatory) pathfinder: science and mission, in *Proc. of the 32nd Inter. Cos. Ray Conf.*, Vol. 8 (2011), p. 243.
 32. J. Nam, S. Ahmad, K. B. Ahn, et al., The UFFO Slewing mirror telescope for early optical observation from gamma ray bursts, *Mod. Phys. Let. A* **28**, 40003 (2013).
 33. I. H. Park, S. Brandt, C. Budtz-Jørgensen, et al., Ultra-Fast Flash Observatory for the obser. of early phot. from gamma-ray bursts, *New Jour. of Phys.* **15**, 023031 (2013).
 34. A. Jung, S. Ahmad, K. B. Ahn, et al., Design and fabrication of detector module for UFFO Burst Alert & Trigger Telescope, in *Proc. of the 32nd Inter. Cos. Ray Conf.*, Vol. 8 (2011), p. 235.
 35. Y.-Y. Chang, C. R. Chen, P. Chen, et al., Inverted-conical light guide for crosstalk reduc. in tightly-packed scintil. matrix and MAPMT assembly, *NIMPA* **771**, 55 (2015).
 36. J. Lee, S. Jeong, J. E. Kim, et al., Design, construction and performance of the detector for UFFO Burst Alert & Trigger Telescope, in *EAS Publication Series, Gamma-ray Bursts: 15 Years of GRB Afterglows*, Vol. 61 (EDP Sciences, UK, 2013), p. 525.
 37. J. Řípa, M. B. Kim, S. Jeong, et al., Testing and performance of UFFO Burst Alert & Trigger Telescope, in *Proc. of Science (SWIFT 10), Swift: 10 Years of Discovery*, (SISSA, 2015), p. 102
 38. P. H. Connell and V. Reglero, The Ultra Fast Flash Observatory pathfinder - UFFO-p GRB imaging and location with its coded mask X-ray imager UBAT, in *EAS Publication Series, Gamma-ray Bursts: 15 Years of GRB Afterglows*, Vol. 61 (EDP Sciences, UK, 2013), p. 517.
 39. S. Jeong, J. W. Nam, K. B. Ahn, et al., Slewing Mirror Telescope optics for the early observation of UV/optical phot. from gamma-ray bursts, *Opt. Expr.* **21**, 2263 (2013).
 40. S. Jeong, J. W. Nam, K. B. Ahn, et al., Development of Slewing Mirror Telescope optical system for the UFFO-pathfinder, in *EAS Publication Series, Gamma-ray Bursts: 15 Years of GRB Afterglows*, Vol. 61 (EDP Sciences, UK, 2013), p. 561.
 41. S. Jeong, S. Brandt, C. Budtz-Jørgensen, et al., Observation of early photons from gamma-ray bursts with the Lomonosov / UFFO-pathfinder, in *III Workshop on Robotic Autonomous Observatories, RevMexAA*, Vol. 45 (UNAM, 2014), p. 139.
 42. J. E. Kim, H. Lim, J. W. Nam, et al., Readout of the UFFO Slewing Mirror Telescope to detect UV/optical photons from gamma-ray bursts *Jour. of Inst.* **8**, P07012 (2013).
 43. M. Panasyuk, Moscow State University satellite "Mikhail Lomonosov" - the multi-purpose obs. in space, in *Proc. of the 32nd Int. Cos. Ray Con.*, Vol. 8 (2011), p.313.
 44. E. Waxman and J. N. Bahcall, High energy neutrinos from cosmological gamma-ray burst fireballs, *Phys. Rev. Let.* **78**, 2292 (1997).
 45. E. Waxman and J. N. Bahcall, Neutrino afterglow from gamma-ray bursts: $\sim 10^{18}$ eV, *ApJ* **541**, 707 (2000).
 46. P. Mészáros and E. Waxman, TeV neutrinos from successful and choked gamma-ray bursts, *Phys. Rev. Let.* **87**, 171102 (2001).
 47. E., Waxman, Astrophysical sources of high energy neutrinos, *Nuclear Physics B Proceedings Supplements* **118**, 353 (2003).
 48. P. Mészáros, Gamma ray bursts as neutrino sources, *arXiv:1511.01396* (2015).
 49. D. Guetta, Neutrinos from gamma ray bursts in the IceCube and ARA era, *Journal of High Energy Astrophys.* **7**, 90 (2015).
 50. R. Abbasi, Y. Abdou, T. Abu-Zayyad, et al., An absence of neutrinos associated with cosmic-ray acceleration in γ -ray bursts, *Nature* **484**, 351 (2012).
 51. M. G. Aartsen, M. Ackermann, J. Adams, et al., Search for prompt neutrino emission from gamma-ray bursts with IceCube, *ApJ* **805**, L5 (2015).